EARTHFLOWS IN THE YANKALILLA AREA OF SOUTH AUSTRALIA: SIGNIFICANCE OF RAINFALL, SOIL PROPERTIES AND MAN'S ACTIVITIES

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VAN DEUR, W. J. (1978) Earthflows in the Yankalilla area of South Australia: significance of rainfall, soil properties and Man's activities. *Trans. R. Soc. S. Aust.* **102**(6), 159-167, 31 August, 1978.

Thirty-three earthflows were located on Permian glacigene deposits east and southeast of Yankalilla, South Australia. Their formation relates to periods of intense, concentrated rainfall when excess soil moisture resulted in deformation by plastic flow. Dating of these earthflows revealed that while all have formed after European settlement, there has been a time-lag between occupance and the majority of mass-movements. The time-lag resulted from alterations in physical and chemical properties of the soil over time, leading to a gradual decrease in shear strength. Soil alterations were initiated by clearing of natural vegetation after settlement.

Introduction

The influence of man on the development of certain landforms is both significant and widespread in many parts of the world. Of particular importance is the acceleration of the processes of erosion resulting from removal of natural vegetation and the subsequent history of land use.

The Fleurieu Peninsula, about 80 km south of Adelaide, South Australia, an area cleared initially in the mid-nineteenth century by European settlers for the cultivation of wheat, clearly shows the repercussion of such enterprise in the form of gullies and mass-movements. It is estimated that these processes have together resulted in a reduction of at least 20% in the amount of available, arable land (Campana, Wilson & Whittle 1954). Thus these processes are of economic as well as geomorphological interest.

In an attempt to elucidate various aspects of the development of these mass-movements, and in particular the relationship between man's activities and landform development, an investigation of 33 examples of mass-movement was carried out in an area of approximately 100 sq. km south and southeast of Yankalilla (Fig. 1).

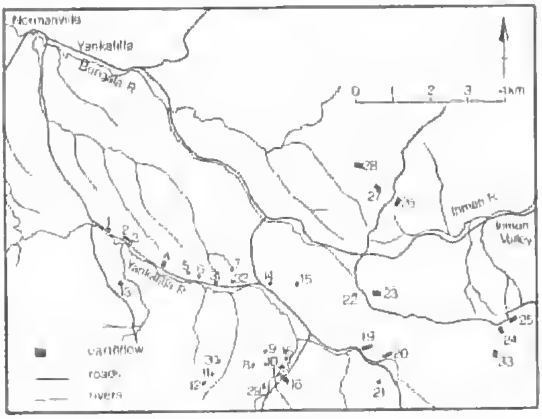

Fig. 1. Location of earthflows.

Found either in isolation or in coalesced groups (Figs 2 & 3), these mass-movements are earthflows as defined by Sharpe (1938) and Varnes (1958), whose classifications are based on the nature and rate of movement and the resultant morphological features. The volume and extent of earthflows varies, but in all instances movement is restricted to depths of 5 m or less. Observed variations in profile are thought to relate to stage of development, with the mature shape comprising a spoon-shaped hollow bounded by a steep, arcuate

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headscarp which becomes more fully inclined at the foot before bulging above the turf surface to form an elongate lobe, extending downslope (Fig. 2). Developing earthflows are distinguished by arcuate tension cracks resulting from subsidence and low level, sub-turf bulging. Older earthflows were located, although in these the main characteristics such as headscarps and lobes have been subdued by subsequent weathering and erosion.

The majority of earthflows are found on overdeepened, glacial depressions, filled with unconsolidated glacial, fluvio-glacial and glacio-lacustrine drift of Permian age, resting unconformably on Precambrian and Cambrian rock (YANKALILLA and JERVOIS map sheets, Geological Atlas One Mile Series; Geol. Surv. S. Aust., Adelaide).

These readily eroded deposits were protected during the Mesozoic planation by virtue of the fact that they lay below the base level of stream incision (Campana, et al. 1954). Evidence for a Mesozoic age for peneplanation is to be found in the presence of a lateritic capping on the present plateau surface. This laterite generally has been considered to be of a Tertiary age (Fenner 1930), but more recent investigations have assigned formation to the Triassic (Daily, Twidale & Milnes 1974; Twidale 1976).

Rejuvenation resulting from Tertiary faulting allowed rivers such as the Yankalilla, Bungala and Inman to cut back into the upland regions. Consequently, the Permian glacigene deposits were eroded and transported more rapidly than the resistant bedrock, thereby forming an area of comparatively low elevation and relief. Slopes developed on these deposits are graded, displaying well developed upper convexities and lower concavities, often separated by long rectilinear sections with an average inclination of 10°.

The resistant uplands comprise heavily metamorphosed and folded Precambrian and Cambrian deposits. In detail these consist of a centrally placed core of Archean micaschists and gneisses upon which the deposits of the Adelaide system rest unconformably. To the east and south, the Kanmantoo group of greywackes, phyllites, quartzitic schists and micaceous quartzites are found.

Several major problems need to be considered in an attempt to explain the development of these earthflows. First, the date of occurrence of each movement must be determined as accurately as possible to establish whether they are relict or modern. Second, in conjunction with this, it is necessary to show if these earthflows are active or dormant, and hence whether they relate to the present system of slope processes, or are evidence of past slope disequilibrium. Finally, their relationship not only to the anthropogenic factor but also to the geological, pedological and climatic controls operating in this region must be established.

Dating of earthflows

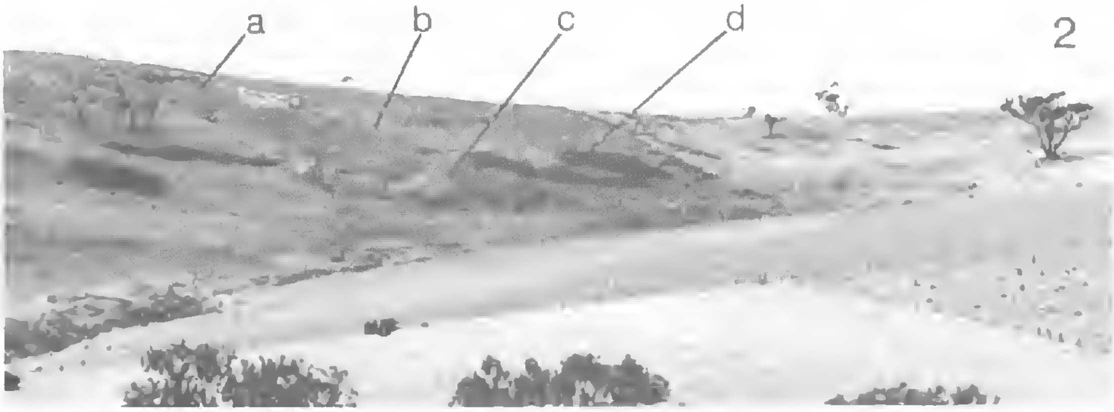
Since the anthropogenic factor has been postulated as one of the major factors influencing the development of these earthflows, it is of some importance to establish as accurately as possible the date of occurrence of each movement. Four dating techniques were employed:

1. Aerial photographs (the first of which were taken in 1949) show the location and morphology of some of the present earthflows. However, because runs were not made in consecutive years, it was possible to assign a particular earthflow to a range of years only.

2. Geological maps of the area (Campana, et al. 1954) indicate 16 'landslides' but do not distinguish type, size or nature of movement. Omissions have been found to occur when comparison was made with the 1949 aerial photographs.

3. Local residents were interviewed and, considering the limitations imposed by migration to and from the area as well as the accuracy of memory, much useful information was obtained. However, for earthflows developed more than ten years ago, it was only possible to assign movements to a range of years.

4. A statistical approach based on rainfall records was used. A recent earthflow was dated with accuracy using the methods outlined, and from this it was possible to calculate the amount of rainfall above the median necessary to produce movement. Years of above median rainfall were extrapolated to indicate periods where earthflowage could have occurred. However, total rainfall is of less importance than the distribution, for when well spaced, excess water can be removed without precipitating mass-movements (Sharpe 1938; Sharpe & Dosch 1942; Crozier 1969; So 1971; Nilsen, Taylor & Dean 1976). The rainfall records were therefore examined for evidence of unusually heavy concentrations.



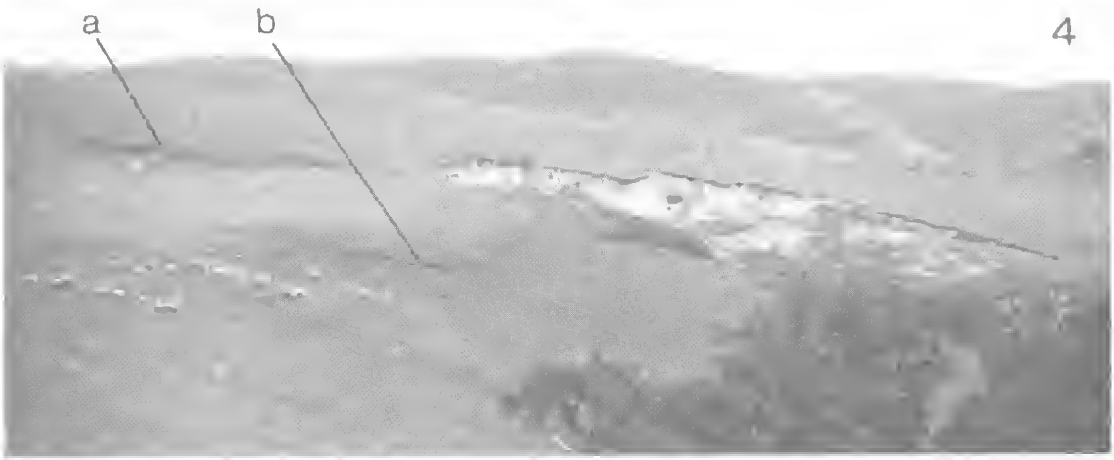


Fig. 2. Single earthflow (No. 9) (a) scarp (b) foot (c) lobe (d) toe.
Fig. 3. Coalesced earthflow (No. 20).
Fig. 4. Earthflow (No. 8) Note the incipient tension crack (a) and subturf bulge (b) to the left of the main movement, corresponding to the scarp and foot of the main earthflow.

TABLE 1
Age and Activity of Earthflows

Ref. No	Age in yrs. (from 1978)	Activity	Slope Angle
1	50+	D	14°
2	50+	D	13°
3	50+	D	12°
4	23	A	12°
5	4	A	11°
6	25–50	E	11°
7	?	D	11°
8	10	A	12°
9	31	A	10°
10	?	E	10°
11	22–23	D	12°
12	4–5	A	9°
13	7	A	11°
14	31–32	D	10°
15	14	A	10°
16	7	A	10°
17	31–32	D	10°
18	50+	E	15°1
19	50+	D	15°
20	22–23	A	16°
21	7	A	9°
22	7	A	9°
23	25–50	A	8°
24	25–50	A	11°
25	?	A	12°
26	10	A	12°
27	25–50	D	20°
28	20–25	A	11°
29	30–50	D	10°
30	?	A	7°
31	25–50	E	11°
32	25–50	E	14°
33	25–50	D	8°
			mean = 10.8°
			S = .92°

A = Active; D = Dormant; E = Extinct.

Twidale (1976) questions such an approach because of the possible variations in rainfall between the recording station and the site of the earthflow. Three points, however, lend validity to the application of the technique in this instance. First, there are a number of recording stations within a small area, with some data extending back over one hundred years, and use has been made of the records of local inhabitants to supplement official records (Mason 1954[1]; Robertson 1975).

Second for the earthflow used as a base, the rainfall data of a farmer about 0.5 km east of the earthflow was compared with the official records and found to be virtually identical. This is not to suggest that variation is not possible, but rather that because of the limited area being considered, this variation is minor. This dating technique is not intended to be used alone, but offers a means of delimiting years of possible movement which, when combined with the other methods, lends a greater degree of accuracy to the results.

The ages and present state of activity of earthflows are presented in Table 1. It is evident that the majority of movements have occurred over the last 50 years, with a large proportion of these post-dating 1945. These earthflows are generally active or in such a state of dormancy that they may be readily reactivated. For example when a portion of the toe of an apparently dormant earthflow was removed during road repair undermining and a consequent surge of the entire lobe occurred.

The time lag between settlement in 1839 and the initiation of widespread mass-movement after 1945 needs explanation. Earthflows probably developed prior to European settlement but on a much smaller scale, as is evidenced by the fact that no mass-movements are to be found on the few remaining areas of natural vegetation once common to the region (Light 1839). The vegetation consisted of savanna woodland on the glacial lowlands (*Eucalyptus leucoxylon; E. camaldulensis* and *E. odorata*) grading to sclerophyll on the plateau surface (Boomsma 1948[2]; Williams 1974). Vegetation was cleared initially for the cultivation of wheat but was later replaced by wattle trees. After 1910 grazing became the predominant form of agricultural activity (Pridham 1955[3]).

Investigation and analysis of earthflow

In order to appreciate the morphology of earthflows in terms of processes operating, an investigation of the physical and chemical properties of earthflow number four was undertaken. This movement, which was shown to have occurred initially in 1955 and developed to its present state in 1956, was selected because it is the largest, single earthflow within the area (although larger are known to have

[1] Mason, B. (1954) "Climatological Survey of the Fleurieu Peninsula". Commonwealth Bureau of Meteorology. (Unpublished).

[2] Boomsma, (1948) Ecology of the Fleurieu Peninsula M.Sc. Thesis, University of Adelaide. (Unpublished).

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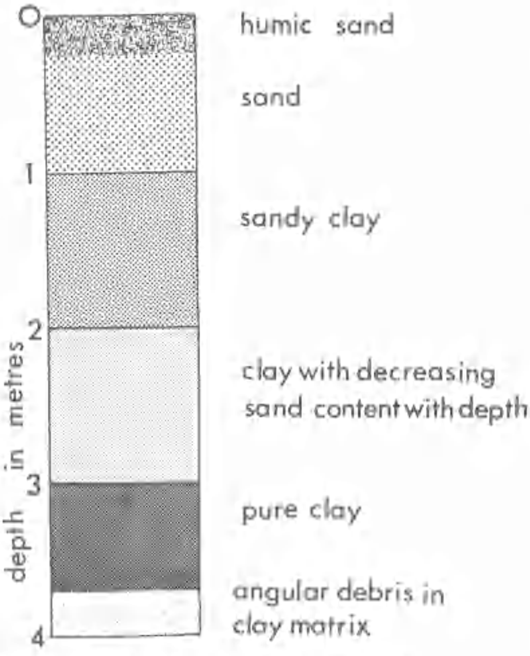

Fig. 5. Composite soil profile diagram.

existed), and it was known to be stable in the lobe zone, although minor headward extension by means of block slumping does occur. Stability was confirmed by eyewitness accounts (D. K. Crawford, per comm.) and by measurements taken over a period of months in winter.

To establish rates of movement, an highly active earthflow was selected (No. 8, Figs 1 & 4). This earthflow formed initially in 1968, and has continued to move downslope, as we found in 1975 and confirmed on subsequent visits in 1976 and 1977. Although smaller overall than earthflow four, measuring 91 m from scarp to toe, and 50 m in width, this earthflow exhibits the classical morphology of such movements.

A composite soil profile (Fig. 5) was established for earthflow four by sinking a series of auger holes on and adjacent to the main body of the movement. In all bores the quartz sand layer extends to an average of 1 m beneath which the percentage of clay increases to a depth of approximately 3.5 m. Below this a layer of highly compressed 'pure' clay is found, which in turn is underlain by a zone of angular debris set in a clay matrix.

Samples were taken at depths of 1.5 and 3 m and tested for variations in sand/clay ratio, and the chemical nature of the clays present analysed by means of X-ray diffraction. These results are presented in Table 2.

TABLE 2
X-ray diffraction analysis

	Bore 1, 1.5m	Bore 2, 3m	Bore 3, 1m
Kaolinite	30–40%	20–30%	10–20%
Illite	20–30%	40–50%	40–50%
Quartz	10–20%	0%	10–20%
Montmorillonite and or randomly stratified material	20–30%	20–30%	20–30%

The most important feature of these results is the decrease in stable kaolinite and quartz with depth, while illite and montmorillonite show an increase. Both of these latter clays are capable of expansion in the presence of moisture. Clay has a low permeability which would cause ground water to be confined, allowing time for absorption into the crystal lattice (this is evident in winter when water-logging of the soils is seen to occur). The saturation conditions produced by heavy rainfall causes swelling and uplift of the over-burden. The instability of the slope is therefore increased.

Observations in gullies and man-made cuttings reveal the presence of such a clay, of varying thickness and at different depths, throughout the area. The role of this clay in the formation of earthflows is therefore considered to be of extreme importance.

The sample from 1.5 m was tested by the Casagrande technique to establish the Atterberg limits of plasticity and liquidity. Adopted from civil engineering, the application of these techniques to the study of mass-movements has been criticized on the grounds that the samples are not in situ. However, the amount of understanding of processes operating derived from the use of the Atterberg limits, warrants their application (see Crozier 1969). The liquid limit of the sample was found to be 38%, the plastic limit 13.5%, and the plasticity index 24.5%. These figures are in accordance with the parameters suggested by Nasmith (1964) for a sandy clay soil formed on glacial deposits (L.L. 41%, PL. 19%).

The water content by weight was found to be 19.79% at 1.5 m and 32.69% at 3 m. In both instances the plastic limit has been surpassed even when Nasmith's higher figure for plasticity is applied), and thus deformation by plastic flow under the influence of gravity may be expected. It is believed, however, that this does not occur until higher water contents, such as occasioned by heavy rainfalls, are experienced, for the slopes upon which earthflows are found are of low to moderate declivity, ranging from 7-16° (Table 1).

Nature and rate of movement

Using the results of the detailed investigations described above, as well as observations on other mass-movements in the area a model to describe the processes operating in the formation of an earthflow can be constructed.

Heavy rainfall results in the subsurface eluviation of fine materials which, along with flowage (probably in the vicinity of the clay layer) causes a disruption in drainage, leading to the formation of a 'soak'. Typically at such locations the ground surface assumes a hummocky appearance. Such disruption is known to have occurred at the present location of earthflow number four as a result of heavy and concentrated rains in both 1946 and 1947. Further rainfall accentuates subsurface flowage, eventually producing a minor subturf bulge. This flow however, subjects the upper slope to tension which, when coupled with subsidence due to eluviation, results in the formation of a tension crack. Such a situation is currently evident adjacent to earthflow number eight (Fig. 4) where the incipient scarp, in the form of a tension crack, corresponds to the main scarp, while subturf bulging is in line with the foot of the main movement. Eventually the lobe breaks the surface at this location, forms a minor recumbent fold, and then slides downslope on a planar glide surface composed of vegetable matter and lubricated by water. This results in the introduction of an auto-catalytic process, since water tends to accumulate in the scarp foot depression. This moisture, along with that which falls directly onto the lobe, is seen to exude from beneath the lobe at the toe.

The rate of motion of the lobe was established by measurements taken during August at three locations along the toe. The results are presented in Table 3. Taking a mean of the motion of the three test lines, the rate of movement is 23 cm/week, or 3.3. cm/day. However, movement is highly variable in response to the amount of rainfall, in summer the lobe being almost stationary. Observations in 1976 and 1977 indicate movement is still occurring and since the slope is constant to the valley floor, movement will continue until this point is attained.

The moisture content of samples taken at the scarp and the toe were found to be 18.5% and 28.13% respectively. The amount of moisture above the plastic limit (Nasmith's figure of 19%) is therefore minor, yet movement as indicated was comparatively rapid, supporting the hypothesis (Skempton 1964) that once an earthflow is set in motion, lower water contents than those necessary to initiate movement can cause a continuation of that movement. Further, as mentioned, flow is replaced to a large extent by planar sliding on a water lubricated surface.

Transversely, differential movement of the lobe is occurring, while a given section of the lobe moves at varying rates over them. This variation over time is explicable by reference to the level of rainfall, but the differential transverse movement poses a problem. It is possible that variations in the physical nature of the material occurs, but observations suggest a homogeneous character. If it is considered that the energy for plastic flow is derived from gravity, and that the degree of energy depends on mass, then where mass is greatest the energy level is greatest. For a given area of sliding surface this is where the lobe has maximum height. The increased friction expected due to greater mass, is compensated by the lubrication provided by the water. Mass however is comprised of not only the materials of the lobe; absorbed water also increases mass and the higher sections of the

TABLE 3
Rates of Movement, Earthflow Eight

	Initial Length Line 1	2	3	Present Length Line 1	2	3	Movement Line 1	2	3
5.viii.75	3.05	3.05	3.05	3.05	3.05	3.05	0	0	0
12.viii.75				2.78	2.96	2.53	0.27	0.09	0.52
17.viii.75				2.65	2.71	2.14	0.12	0.24	0.40
22.viii.75				2.53	2.56	1.98	0.12	0.15	0.15

* Observations taken 30.x.75 showed line three to be completely covered. Movement of over 3.05 m has therefore occurred.

lobe have the potential to retain more moisture. Once in motion these sections of the lobe also possess a greater energy and thus will continue to move after the cessation of rainfall.

Earthflows increase their dimensions after the initial flow largely by movement of the lobe, but headward extension also occurs. This is mainly by means of block slumping at the scarp due to lateral pressure release, but may also occur by means of secondary earthflow, as found on earthflow number four in 1974.

Factors producing earthflows

In attempting to assign a process to mass-movement, the cause of individual earthflows is considered, although Varnes (1958) states: 'In most cases a number of causes exist simultaneously and so attempting to decide which one finally produced failure is not only difficult, but also incorrect. Often the final factor is no more than a trigger that sets in motion an earthmass that was already on the verge of failure.'

When analysing earthflows within the area, an association is established with high rainfall, but in fact it is a combination of climate, geology, soil properties and the role of man. All these variables must be considered.

For motion to have occurred, shear stress must have exceeded shear strength, that is the resistance of the soil to stress. Shearing strength in a normally unconsolidated soil is dependent upon the cohesion between soil particles and friction due to granular interlocking of these particles. A sandy soil which possesses negligible cohesion, has high levels of internal friction which in turn allows a high angle of repose. In comparison clay has low internal friction but high levels of cohesion. For slope failure to occur, two factors must act, singularly or in conjunction; either stress is increased beyond shear strength, or the latter is reduced. In the study area the major causes of mass-movement is a decrease in shear strength. Short term stresses, such as produced by seismic activity, were found to be of little or no consequence. However, long term stresses resulting from the loading of soil during heavy rainfall may be considered a triggering factor and therefore relate to the climatic charateristics of the Fleurieu Peninsula. These have been determined from records kept since about 1850 both officially and by local farmers (Mason 1954; Robertson 1975).

Distribution of rainfall fluctuates according to the season and with topography, the main source being frontal uplift during the winter months which, when accentuated by topography on the western margins of the Peninsula, results in annual falls of up to 900 mm. Within the area where the majority of earthflows are found, rainfall ranges from 550 mm along the coast in the vicinity of Normanville to 750 mm near Inman Valley.

Since unusually heavy concentrations of rainfall in short periods of time are more likely to lead to mass-movements, it is necessary to know the median amounts of rainfall, and relate these to the actual amount which fell at the time an earthflow was initiated. In winter the median is 250 mm, while in summer this decreases to 63 mm (Mason 1954). This summer figure is of greater importance when taken in conjunction with the amount of moisture required to prevent the loss of soil water (150 mm). This exceeds the amount of rainfall in the upper quartile range (125 mm) so that summer desiccation is to be expected. The opening of the surface layers of soil is considered to be of utmost importance, for it allows the deep penetration of moisture when the first rains fall, usually in April.

The major cause of earthflows is a decrease in the shear strength of the soil, and the shear strength of these glacigene deposits varies with sand/clay ratio and the degree of compaction. The superficial sand layers lack intergranular cohesion, but are held by intergranular friction and adhesion by water. Bulking of the sand allows a higher than normal angle of repose which, when coupled with the non-plastic nature of sand, results in there being no earthflows involving sand alone. The increasing clay content with depth is responsible for the plastic qualities of the soil, and it is a direct result of a decrease in cohesion of this clay that earthflows occur. A number of factors are responsible for this reduction in shear strength due to a decrease in cohesion, although the anthropogenic factor is of utmost importance.

The process of wetting and drying, which causes expansion and contraction of the illite and montmorillonite lattice, over time significantly reduces the cohesive force between clay particles. Desiccation is a common occurrence during summer months, when evaporation exceeds precipitation, not only on the body of the earthflow, but on the stable surrounding slopes of the area. Where an overburden of sand is present, capillary removal of ground water is sufficient to produce subsurface desiccation. Further, the cohesive strength of clay decrease with an increase of soil moisture, and thus the subsequent replacement of groundwater, causes an increase in pore-water pressures which brings about a further loss of cohesion as the normal intergranular forces are taken up by the interstitial water. The superincumbent mass of soil is therefore partially supported by this groundwater, resulting in a further decrease in shear strength.

Failure, as has been demonstrated by Skempton (1948), is not immediate and is considered to vary with slope, ranging from 6 weeks in the case of a highly colloidal clay at 90° to 50 years on a clay slope of 18°. Acknowledging the differences in clay type and proportions, it is felt that the low slope angles in the area contribute to the time lag between the clearing of vegetation and earthflow.

Cohesion is also reduced as a consequence of clearing, as a change to the clay-humus colloid results from base exchange. Humus has the important role of improving soil texture and structure by the creation of granular aggregates. These aggregates are destroyed with the loss of humus and the replacement by sodium ions. More importantly however, humus has the propensity to absorb 80-90% of its own weight in water, whereas clays can absorb only 15-20%. If a sufficient quantity of humus exists, rainfall is retained in the surface layer to a certain degree, thereby decreasing the amount of water in contact with the substratum. Since earthflow occurs at this level by plastic deformation, it is probable that the humus layer slows or prevents the attainment of plasticity. During summer months, water is retained by the humus and thus desiccation is reduced.

It has been suggested that vegetation stabilises slopes by root anchorage. Various studies have indicated the relationship between mass-movements and the depth and type of root systems (Rice, Corbett & Bailey 1969). So (1971) however, doubts whether this relationship is a clear cut as suggested, and infers that vegetation holds only the surface layers, and allows plastic deformation at a lower depth.

Within the area under discussion, the role of vegetation is vitally important. No large scale mass-movements are discernible on the little remaining vegetation, although minor movement has occurred in earthflow number twelve, where isolated trees and gorse are found. Rafting of trees was limited. Overall, therefore, earthflows are located on cleared slopes, while some have been stabilised by revegetation.

The time lag between clearing and subsequent earthflow is attributed to a number of factors. Because of low general slope angle gravitational shear stress is limited. More importantly, the cohesion supplied by the clay and clay-humus colloid decreased gradually over time by wetting and drying and base change on the clay-humus colloid. The holding power of roots was lost at an early stage, but earthflow did not occur until shear stress exceeded shear strength. Increased shear stress resulted from saturation of the soil produced by intense rainfall over short periods of time. Once movement causes minor subsidence, a water trap is formed and thus an autocatalytic process eventuates. Why an earthflow occurred at one point and not another may be related to minor differences in soil profile, rates of loss of cohesion in clay, the deterioration of the clay-humus colloid and ultimately the time of clearing of vegetation by European settlers.

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